Fully supersymmetric CP violations in the kaon system

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We show that, on the contrary to the usual claims, fully supersymmetric CP violations in the kaon system are possible through the gluino mediated flavor changing interactions. Both ϵ_K and $\mathrm{Re}(\epsilon'/\epsilon_K)$ can be accommodated for relatively large $\tan\beta$ without any fine tunings or contradictions to the FCNC and EDM constraints.

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Until this year, the only CP violation observed was in $K_L \to 2\pi$ [1], which could be attributed to $\Delta S = 2$ $K^0 - \overline{K^0}$ mixing. The mixing parameter ϵ_K is accurately measured by now : $\epsilon_K = e^{i\pi/4}\ (2.280 \pm 0.013) \times 10^{-3}$ [2]. Recent observation of $\mathrm{Re}(\epsilon'/\epsilon_K)$ by KTeV collaboration, $\mathrm{Re}(\epsilon'/\epsilon_K) = (28 \pm 4) \times 10^{-4}$ [3], nicely confirms the earlier NA31 experiment [4] $\mathrm{Re}(\epsilon'/\epsilon_K) = (23 \pm 7) \times 10^{-4}$. This nonvanishing number indicates unambiguously the existence of CP violation in the decay amplitude ($\Delta S = 1$). These two parameters quantifying CP violations in the kaon system can be accommodated by the KM phase in the Glashow-Salam-Weinberg's standard model (SM). The SM prediction for the latter is about 5×10^{-4} and lies in the lower side of the data, although theoretical uncertainties from nonperturbative matrix elements and the strange quark mass are rather large [5].

However, it would be interesting to consider a possibility that these CP violations have their origin entirely different from the KM phase in the SM, in particular in the framework of various extensions of the SM including supersymmetric models [6]. In the minimal supersymmetric standard model (MSSM) considered in this work, there are many new CP violating phases that fall into two categories : phases with flavor preserving (FP) and flavor changing (FC), each of which is constrained by electron/neutron electric dipole moments (EDM's) and the ϵ_K, respectively. Recently, it was shown that the FP and CP violating phases in A_t and μ in the more minimal SUSY model do not generate enough ϵ_K [7] [8] or new phase shift in $B^0 - \overline{B^0}$ [7] [9], although they can lead to a large direct CP asymmetry in $B \to X_s \gamma$ upto $\sim \pm 16\%$ if charginos and stops are light enough [9]. However, another class of CP violating phases in the flavor changing quark-squark-gluino vertices in the MSSM may be relevant to CP violations in the K meson system.

In this letter, we show that all the observed CP violating phenomena in the kaon system in fact can be accommodated in terms of a single complex number $(\delta_{12}^d)_{LL}$ that parameterizes the squark mass mixings in the chirality and flavor spaces for relatively large $\tan\beta$ without any fine tuning or any contradictions with experimental data on FCNC, even if $\delta_{\rm KM} = 0$. We assume that CKM matrix is real in the most of this letter for simplicity and maximizing the effect of our mechanism. The case where the KM phase is nonzero is discussed in brief, and the details will be given elsewhere [10].

In order to study the gluino (photino) mediated flavor changing phenomena in the quark (lepton) sector such as $\Delta m_K, \epsilon_K$ and $\mathrm{Re}(\epsilon'/\epsilon_K)$ or lepton flavor violations, it is convenient to use the so-called mass insertion approximation (MIA) [11]. The quark-squark-gluino vertex is flavor diagonal in the MIA, and the flavor/chirality mixing occur through the insertion of $(\delta_{ij}^d)_{AB}$, where $i, j = 1, 2, 3$ and $A, B = L, R$ denote the flavors of the squark under consideration and the chiralities of its superpartner. The superscript denotes that the down type squark mass matrix is involved. The parameters $(\delta_{ij}^d)_{AB}$ characterize the size of the gluino-mediated flavor changing amplitudes, and they may be CP violating complex numbers, in general. In the following, diagrams involving charged Higgs, chargino and neutralino will be ignored, since they are suppressed by α_w/α_s compare to the gluino-squark loops unless gluino/squarks are very heavy. This should be a good starting point for studying the SUSY FCNC/CP problems.

Now, if one saturates Δm_K and ϵ_K with $(\delta_{12}^d)_{LL}$ alone, the resulting $\mathrm{Re}(\epsilon^{'}/\epsilon_K)$ is too small by more than an order of magnitude, unless one invokes some finetuning [12]. Recently, Masiero and Murayama showed that this conclusion can be evaded in generalized SUSY models [13] with a few reasonable assumptions on the size of the $(\delta_{12}^d)_{LR}$ and the relations between the down quark Yukawa couplings and the CKM mixings. But they did not consider possibility to generate ϵ_K from a supersymmetric phase in Ref. [13], and also predict too large neutron EDM which is very close to the current upper limit.

In the following, we show that there is another *generic* way to saturate $\epsilon^{'}/\epsilon_K$ in supersymmetric models if $|\mu\tan\beta|$ is relatively large, say $\sim 10 - 20$ TeV. Moreover, both ϵ_K and $\mathrm{Re}(\epsilon^{'}/\epsilon_K)$ can be generated by a single CP violating complex parameter in the MSSM. In other words, fully supersymmetric CP violations are possible in the kaon system. The argument goes as follows : if $|(\delta_{12}^d)_{LL}| \sim O(10^{-3} - 10^{-2})$ with the phase $\sim O(1)$ saturates ϵ_K, this same parameter can lead to a sizable $\mathrm{Re}(\epsilon'/\epsilon_K)$ through the $(\delta_{12}^d)_{LL}$ insertion followed by the

FP (LR) mass insertion, which is proportional to

$$(\delta^d_{22})_{LR} \equiv m_s(A^*_s - \mu\tan\beta)/\tilde{m}^2 \sim O(10^{-2}),$$

where $\tilde{m}$ denotes the common squark mass in the MIA. It should be emphasized that the induced $(\delta^d_{12})^{\rm ind}_{LR} \equiv (\delta^d_{12})_{LL} \times (\delta^d_{22})_{LR}$ is different from the conventional $(\delta^d_{12})_{LR}$ in the literature. The loop functions for these two LR insertions are different with each other in general. The LR mixing $(\delta_{12})^{\rm ind}_{LR}$ induced by $(\delta^d_{12})_{LL}$ is typically very small in size $\sim O(10^{-5})$, but this is enough to generate the full size of ${\rm Re}(\epsilon'/\epsilon_K)$ as shown below. Our spirit to generate supersymmetric ${\rm Re}(\epsilon^{'}/\epsilon_K)$ is different from Ref. [13], where the LR mass matrix form is assumed to be similar to the Yukawa matrix so that they predict the neutron EDM to be close to the current upper limit. On the other hand, our model does not suffer from the EDM constraint at all, as shown below.

Let us first consider the gluino-squark contributions to the $K^0-\overline{K^0}$ mixing due to two insertions of $(\delta^d_{12})_{LL}$. The corresponding $\Delta S = 2$ effective Hamiltonian is given by

$$\mathcal{H}_{\rm eff}(\Delta S = 2) = C_1 \overline{d}^\alpha_L \gamma_\mu s^\alpha_L \; \overline{d}^\beta_L \gamma^\mu s^\beta_L$$

with the Wilson coefficient C_1 being

$$C_1 = -\frac{\alpha_s^2}{216\widetilde{m}^2}(\delta^d_{12})^2_{LL}\left[24 x f_6(x) + 66\widetilde{f}_6(x)\right]. \qquad (1)$$

Here, $x = m^2_{\tilde{g}}/\tilde{m}^2$ and the loop functions $f_6(x)$ and $\widetilde{f}_6(x)$ are given in [14]. The double mass insertion diagrams of FC LL followed by the FP LR generate another operators : $\widetilde{Q}_2 = \overline{d}^\alpha_L s^\alpha_R \overline{d}^\beta_L s^\beta_R$ and $\widetilde{Q}_3 = \overline{d}^\alpha_L s^\beta_R \overline{d}^\beta_L s^\alpha_R$, whose Wilson coefficients are proportional to $\left[(\delta^d_{12})^{\rm ind}_{LR}\right]^2$.Since their effects on Δm_K and ϵ_K are negligible, we do not show them here explicitly although their effects have been included in the numerical analyses.

Now we turn to the $\Delta S = 1$ effective Hamiltonian $\mathcal{H}_{\rm eff}(\Delta S = 1) = \sum_{i=3}^8 C_i \mathcal{O}_i$. The sdg operator O_8 which is relevant to ${\rm Re}(\epsilon^{'}/\epsilon_K)$ is defined as

$$\mathcal{O}_8 = \frac{g_s}{4\pi} m_s \overline{d}^\alpha_L \sigma^{\mu\nu} T^a s^\alpha_R G^a_{\mu\nu}, \qquad (2)$$

and other four quark operators $O_{i=3,\ldots,6}$ and the corresponding Wilson coefficients from C_3 to C_8 with a single mass insertion are available in the literature [14]. One has to remind that $C_{3,\ldots,6}$'s are proportional to $(\delta^d_{12})_{LL}$, whereas C_8 is given by a linear combination of $(\delta^d_{12})_{LL}$ and $(\delta^d_{12})_{LR}$. This $(\delta^d_{12})_{LR}$ dependent part in C_8 is proportional to $m_{\tilde{g}}/m_s$, and thus is very important for generating ${\rm Re}(\epsilon^{'}/\epsilon_K)$ even if $(\delta^d_{12})_{LR}$ is fairly small.

If we consider the penguin diagram Fig. 1 with the double mass insertion, the Wilson coefficient C_8 is given by

$$C_8^{(2)} = \frac{\alpha_s}{\widetilde{m}^2}\frac{m_{\widetilde{g}}}{m_s}(\delta^d_{12})^{\rm ind}_{LR}\left[\mathcal{C}_1 M_1^{(2)}(x) + \mathcal{C}_2 M_2^{(2)}(x)\right], \quad (3)$$

where $\mathcal{C}_1 = 3/2, \mathcal{C}_2 = -1/6$ and

$$M_1^{(2)}(x) = \frac{2(3 - 3x^2 + (1 + 4x + x^2)\log x)}{(x-1)^5}$$
$$M_2^{(2)}(x) = \frac{1 + 9x - 9x^2 - x^3 + 6x(1+x)\log x}{(x-1)^5}. \qquad (4)$$

The contributions of photon penguin and Z penguin diagrams with the double mass insertion are negligible as in the case of the single mass insertion [14].

Now we are ready to calculate the SUSY contributions to $\Delta m_K, \epsilon_K$ and ϵ'/ϵ_K using the $\Delta S = 1,2$ effective Hamiltonians obtained above and the following expressions [15]:

$$\Delta m_K({\rm SUSY}) = 2{\rm Re}M_{12},$$
$$\epsilon_K({\rm SUSY}) = \frac{\exp(i\pi/4)}{\sqrt{2}\Delta m_K({\rm exp})}\;{\rm Im}M_{12}, \qquad (5)$$
$${\rm Re}(\epsilon'/\epsilon_K) = \frac{\omega}{\sqrt{2}|\epsilon_K|{\rm Re}A_0}\sum_i {\rm Im}(C_i)\langle O_i\rangle_0(1 - \Omega_{\eta+\eta'})$$

where $2m_K M^*_{12} \equiv \langle \bar{K}^0|H^{\Delta S=2}_{eff}|K^0\rangle$ and A_I's are the isospin amplitudes defined as $A_I e^{i\delta_I} \equiv \langle(\pi\pi)_I|\mathcal{H}^{\Delta S=1}_{\rm eff}|K^0\rangle$. In the numerical analysis, we use the same parameters as in Ref. [15] with $m_s(2{\rm GeV}) = 130{\rm MeV}$. The corresponding SM prediction for ${\rm Re}(\epsilon^{'}/\epsilon_K) = 5.7 \times 10^{-4}$. We vary the modulus and the phase of $(\delta^d_{12})_{LL}$ as indepent parameters, and select those points which satisfy $\Delta m_K({\rm SUSY}) \lesssim \Delta m_K({\rm exp})$ and $|\epsilon_K({\rm SUSY}) - \epsilon_K({\rm exp})| < 1\sigma$. Then, for these points, we plot ϵ'/ϵ_K in Figs. 2 (a)–(d) as functions of the modulus r [(a) and (c)] and the phase φ [(b) and (d)] of the parameter $(\delta^d_{12})_{LL} \equiv re^{i\varphi}$ for the common squark mass $\tilde{m} = 500$ GeV. The upper (lower) rows correspond to $\widetilde{A_s} \equiv (A_s - \mu^*\tan\beta) = -10\ (-20)$ TeV. Different x's ($=$ 0.3, 1.0, 2.0) are represented by the solid, the dashed and the dotted curves, respectively. If we choose the opposite sign for $\widetilde{A_s}$, the phase of the relevant $(\delta^d_{12})_{LL}$ should be shifted by 180° in order that we have correct sign for ϵ_K. From Figs. 2 (a) and (b), it is clear that both ϵ_K and ${\rm Re}(\epsilon'/\epsilon_K)$ can be nicely accommodated with a single complex number $(\delta^d_{12})_{LL}$ with $\sim O(1)$ phase in our model without any difficulty, if $|\mu|$ and $\tan\beta$ is relatively large so that $|\widetilde{A_s}|$ becomes a few tens of TeV. If the common squark mass $\tilde{m}$ differs from 500 GeV, the $\widetilde{A_t}$ should be multiplied by $(\tilde{m}$ in GeV$/500)^2$ for the fixed x.

Let us consider the neutron EDM constraint. The FP LR mass insertion in the gluino-squark diagram contributes to the neutron EDM. The effective Hamiltonian for the neutron EDM is given by [16] $\mathcal{H}_{eff}({\rm EDM}) = \sum_{i=1}^3 C_i^{\rm edm} O_i$, where the O_i's are defined as

$$O_1 = -\frac{i}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 f F_{\mu\nu},$$
$$O_2 = -\frac{i}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 T^a f G^a_{\mu\nu},$$
$$O_3 = -\frac{1}{6} f_{abc} G^a_{\mu\rho} G^{b\rho}_{\ \ \nu} G^c_{\lambda\sigma}\epsilon^{\mu\nu\lambda\sigma}. \qquad (6)$$

In our model, the FP LR mass insertion in the gluino-squark diagram contributes to the neutron EDM with the following Wilson coefficients :

$$C_1^{\rm edm} = -\frac{2}{3}\,\frac{e\alpha_s}{\pi}\,Q_d\,\frac{m_{\tilde g}}{\widetilde{m}^2}\,{\rm Im}\left(\delta_{11}^d\right)_{LR}\,B^{(1)}(x),$$
$$C_2^{\rm edm} = \frac{g_s\alpha_s}{4\pi}\,\frac{m_{\tilde g}}{\widetilde{m}^2}\,{\rm Im}\left(\delta_{11}^d\right)_{LR}\,C^{(1)}(x), \qquad (7)$$

where $(\delta_{11}^d)_{LR} \equiv m_d(A_d^* - \mu\tan\beta)/\widetilde{m}^2$, and

$$B^{(1)}(x) = \frac{1+4\,x-5\,x^2+2\,x\,(2+x)\,\log(x)}{2\,(-1+x)^4}, \qquad (8)$$
$$C^{(1)}(x) = \frac{2\,\left(-11+10\,x+x^2\right)-\left(9+16\,x-x^2\right)\,\log(x)}{3\,(-1+x)^4}.$$

and $C_3^{\rm edm} = 0$. Our expression for $C_1^{\rm edm}$ confirms the result obtained in Ref. [14], and the result for $C_2^{\rm edm}$ is new. The renormalization group (RG) running effect and the final formula for the neutron EDM can be found in [16]. We found that the EDM constraint is very strong. If the universality of the trilinear couplings are assumed ($A_d = A_s$), then $\left(\delta_{11}^d\right)_{LR}$ should be essentially real. Still a single CP violating phase in $(\delta_{12}^d)_{LL}$ can generate right amounts of ϵ_K and ${\rm Re}(\epsilon'/\epsilon_K)$ without any fine tuning. Even if we relax the universality condition $A_d = A_s$, the result is basically the same, since we are in the regime of large $\mu\tan\beta$ and its phase is constrained by the neutron EDM irrespective of $A_d = A_s$ as long as $|A_{d,s}| \lesssim 1$ TeV. Note that we are not assuming any specific flavor structures in the A terms at all, unlike many other models in Ref. [6].

It should be worthwhile to emphasize the importance of the FP(LR) mixing $(\delta_{22}^d)_{LR}$ in our study. If we ignored this effect and considered the flavor changing (LL) and (RR) mixings simultaneously for example, we could get both ϵ_K and ${\rm Re}(\epsilon'/\epsilon_K)$, but significant amounts of fine tunings are unavoidable. The ratio of the magnitues of $(\delta_{12}^d)_{LL}$ and $(\delta_{12}^d)_{RR}$ should be $\mathcal{O}(10^{-3})$ in order that we explain the large experimental data for ${\rm Re}(\epsilon'/\epsilon_K)$. Then, the contributions from $(LL)^2$ [or $(RR)^2$, whichever the larger one] and $(LL)\times(RR)$ terms should cancel with each other within a part in 10^3 in order to reproduce the experimental value for ϵ_K, thus requiring substantial fine tuning [10].

If the simplifying assumption of the real CKM matrix is relaxed, there will be additional constributions to ϵ_K and ${\rm Re}(\epsilon'/\epsilon_K)$ from the SM and other SUSY loop diagrams. If we assume that only the gluino-squark contribution considered above is comparable with the SM contribution, it would be possible that the ϵ_K is mainly dominated by the KM phase contributions, but the ${\rm Re}(\epsilon'/\epsilon_K)$ has significant contributions from the induced $(\delta_{12}^d)_{LR}$ as disucssed in this letter [10].

The best discriminant between our model and the SM model would be probably the branching ratios for $K\to\pi\nu\nu$ and CP violations in B decays. The branching ratio for the decay $K_L\to\pi^0\nu\bar\nu$ is essentially zero in our model, since it is purely CP violating but there is no appreciable CP violation in the $s\to d\nu\bar\nu$ amplitude through gluino loop diagram [14]. On the contrary, $K^+\to\pi^+\nu\bar\nu$ involves both CP conserving and CP violating amplitudes, and the corresponding branching ratio in our model ranges over $(8.9\pm7.2)\times10^{-11}$, compared to the SM prediction : $B(K^+\to\pi^+\nu\bar\nu)_{\rm SM} = (7.7\pm3.0)\times10^{-11}$ [17]. Our predictions can be changed by two ways, however. The chargino-upsquark loop contributions contribute to $K\to\pi\nu\bar\nu$ through the enhanced sdZ penguin vertex, but one still expects the branching ratio for $K_L\to\pi^0\nu\bar\nu$ to be smaller than the SM predictions [18]. Also, if our assumption on the real CKM matrix is relaxed, the KM phase will contribute to the $K\to\pi\nu\bar\nu$, but the predictions will differ from the SM, since there is additional contribution to ϵ_K so that the CKM elements are less constrained [10]. If we stick to $\delta_{KM} = 0$, the CP violations in B system will be very different from the SM predictions. However, the gluino-squark loop contributions to the B system is governed by new parameters, $(\delta_{13}^d)_{AB}$ and $(\delta_{23}^d)_{AB}$, which are independent of $(\delta_{12}^d)_{AB}$ we considered here. Therefore we cannot make defninte predictions for B decays. Generically the situation could be very different from the SM case [19].

Now let us consider a typical size of $(\delta_{12}^d)_{LL}$ in the MSSM. The answer to this question would depend on the models for soft SUSY breaking and how to solve the SUSY flavor problem. If one invokes approximate (abelian or nonabelian) flavor symmetry in order to solve the SUSY FCNC problem, the natural size of $(\delta_{12}^d)_{LL}$ could be order of $\sim(\lambda^3-\lambda^4)\sim10^{-3}$ with order $O(1)$ phase (where $\lambda = \sin\theta_c = 0.22$) [20]. This is usually referred as the alignment in contrast to more popular universality. This is in fact the twisted version of the so-called SUSY FCNC and SUSY ϵ_K problem, saying that the gluionic SUSY contribution to ϵ_K could be generically very large unless the squarks are degenerate and/or the mass matrices of quarks and squarks are almost aligned in the flavor space. In this context, our result on ϵ'/ϵ_K is nothing but to say that SUSY ϵ_K problem in general implies the SUSY ϵ' problem for relatively large $|\mu\tan\beta|\sim O(10)$ TeV.

In conclusion, we showed that both ϵ_K and ${\rm Re}(\epsilon'/\epsilon_K)$ can be accommodated with a single CP violating and flavor changing down-squark mass matrix elements $[(\delta_{12}^d)_{LL}\sim10^{-3}]$ without any fine tuning or any conflict with the data on FCNC processes, if $|\mu\tan\beta|\sim10-20$ TeV with a scale factor $[\tilde m({\rm in\ GeV})/500]^2$ for the fixed x. Our mechanism utilizes this FC LL mass insertion along with the FP LR mass insertion propotional to $(\delta_{22}^d)_{LR}\sim10^{-2}$. The latter is generically present in any SUSY models including the MSSM, and thus there is no fine tuning in our model for accommodating both ϵ_K and ${\rm Re}(\epsilon'/\epsilon_K)$ in terms of a single $(\delta_{12}^d)_{LL}$. It is straightforward to extend our mechanism including the nonvanishing KM phase, $(\delta_{12}^d)_{LR}$ and/or $(\delta_{12}^d)_{RR}$. One can also consider our mechanism in the more minimal SUSY model, where $(\delta_{22})_{LR}^d$ is proportional to $m_b(A_b-\mu\tan\beta)$

so that $A_b - \mu \tan\beta$ may be lowered significantly. All these finer details including $B(K \to \pi\nu\bar{\nu})$ will be discussed elsewhere in the forthcoming publication [10].

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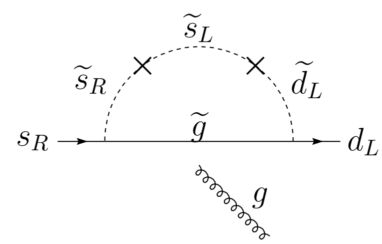

FIG. 1. Feynman diagram for $\Delta S = 1$ process. The cross denotes the flavor changing (LL) and the flavor preserving (LR) mixings, respectively.

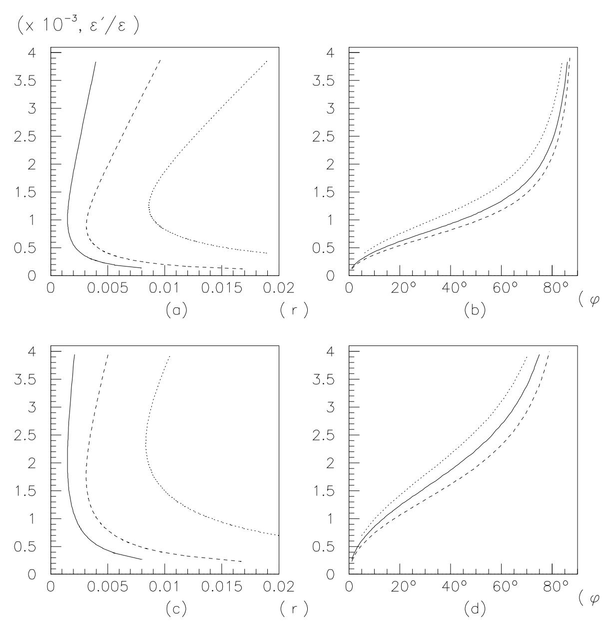

FIG. 2. $Re(\epsilon'/\epsilon_K)$ as a function of the modulus r [(a) and (c)] and the phase φ [(b) and (d)] of the parameter $(\delta^d_{LL})_{12}$ with $\widetilde{A}_S$ to be $-10\ TeV$ ((a),(b)) and $-20\ TeV$ ((c),(d)). The common squark mass is chosen to be $\widetilde{m} = 500$ GeV, and the solid, the dashed and the dotted curves correspond to $x = 0.3,\ 1.0,\ 2.0$, respectively.